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JAAKKO SALOKANGAS · P. LEHTO

On the fatigue strength of a copper coating sprayed on steel bars

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ON THE FATIGUE STRENGTH OF A COPPER COATING SPRAYED ON STEEL BARS

JAAKKO SALOKANGAS · P. LEHTO

HELSINKI 1959

CPI - COMMISSION PERMANENTE INTERNATIONALE DE L'ACETYLENE ET DE LA SOUDURE AUTOGENE has awarded this paper the second prize in the C.P.I. Second International Competition.

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1. THE METALLIZED COATING

Metallizing is a process by which molten metal atomized into a fine spray is sprayed onto the surface to be coated. Usually the molten metal is atomized and discharged with the aid of air or some other gas. The mean temperature of the metal

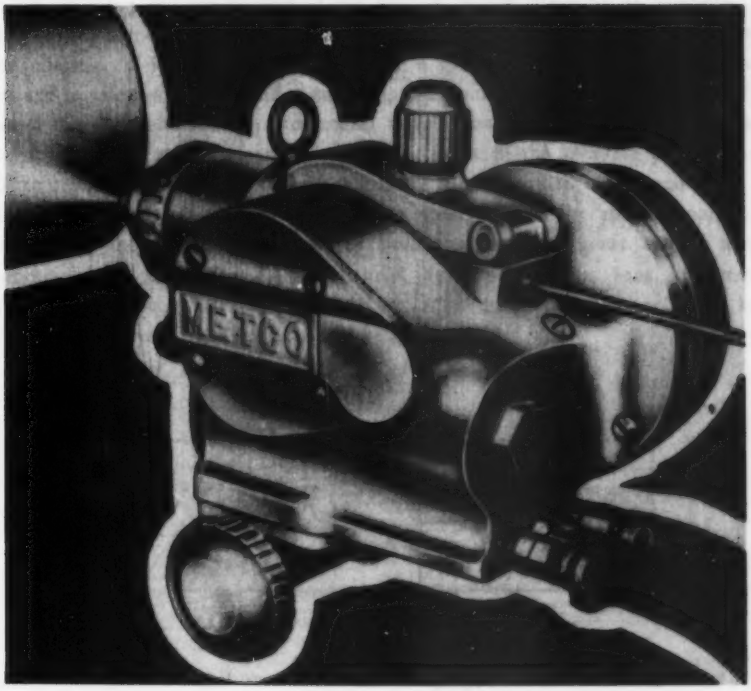


Fig. 1. Metallizing gun.

spray is often considerably low because the spray is composed of a relatively small amount of atomized metal particles and a large amount of cool gas [3].

In coppering the steel bars by spraying, the authors have employed the Metco type U metallizing gun. The wire is melted in an acetylene-oxygen flame and the atomizing and discharging are effected with the aid of compressed air. The work proceeds in the way shown in Fig. 1. The metallizing gun has been fastened to the carriage of the lathe and the test bar is circulating in the lathe between the centres. The number of revolutions and the speed of the carriage are regulated depending on the thickness of the successive layers.

2. THE PROPERTIES OF THE COATINGS AND THE BONDING TO THE BASE MATERIAL

In order that the coating may serve its purpose, i.e., be a protection against corrosion, it should be sufficiently dense and thick. To ensure good bonding, thorough cleaning and roughening of the surface before spraying is required. The right operating direction of the spray gun is of great importance to the proper bonding of the coating. It is then possible to avoid, e.g., shadows formed by the thread ridges and to effect a perpendicular spray inpingement to the work surface. In Fig. 2 is shown the different behaviour of metal layers sprayed on threaded and smooth surfaces. The shear strength may become very great in the spraying process, e.g., owing to expansion by heat. The threads fold the elementary layers up and down thus reducing the danger of splitting. It has been observed that the strength parallel to the surface of the sprayed layer may be even ten times as great as the strength perpendicular to the surface. Consequently, by threading the base the strength parallel to the surface will be utilized [1]. This is very important when heavy coatings are sprayed on stressed specimens.

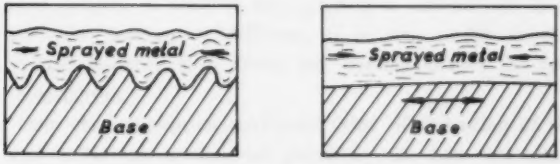


Fig. 2.

Sprayed metal over threads. Shrink restrained by threads.

Sprayed metal on smooth surface. Shear stress due to shrink.

Owing to porosity and oxide content the structure of a sprayed copper surface becomes heterogeneous. However, its resistance to wear, the relatively great hardness and an advantageous bonding render it a suitable coating. Because of the porosity of the sprayed copper coating, opinions vary about its capacity to protect the roll against corrosion. The general opinion is that a machined coating 1.5 mm thick is watertight [1]. If the protection is not perfect, corrosion gains ground owing to the cathodic nature of copper.

Although sufficient safety should have been obtained with regard to porosity, cracks which may appear during application can cause unpleasant surprises. This bas brought up the question about the possible fatigue of sprayed copper and factors which are affecting it.

3. EXAMINATION OF THE PROPERTIES FROM THE STANDPOINT OF FATIGUE STRENGTH

When examining the fatigue of materials, it has been observed that a heterogeneous structure is in general more susceptible to fatigue failure. On the other hand, it should be observed that a material such as this which is inhomogeneous in its internal structure is rather insensitive with regard to external notch sensitivity. In application its properties appear to advantage when a homogeneous material is suffering from the influence of the notch. However, it should be observed that the sprayed coating is never alone the sole bearing element. The frame itself, the base, receives the main part of the stresses. If we examine the base coated with copper and the factors that cause fatigue under service conditions, it is to be expected that just the defective points are susceptible to fatigue and the starting points for possible failure. The capillarity of the pores has an influence of its own on the fatigue. This influence is greatest when the moisture is allowed to proceed through the thin coating as far as the steel. But, although the sprayed layer is formed without uniting channels between the steel and the surface, the base layer between steel and copper has still its own significance in spite of that. If the spraying is carried out in different ways on the steel frame, the bonding is different. It is thus to be expected that the smoothness of the zone between base metal and coating affects the fatigue strength of the whole construction.

If we set out from the assumption that some kind of threading of the test bar is an acceptable and sufficient method of preparing the base material, there still remain a large number of factors that may affect the spraying result and the fatigue strength. Such factors connected with the spraying proper are, e.g., spraying distance, speed of the wire feed, the mixing ratio and pressures of oxygen and acetylene, the pressure of the atomizing air and changes in the temperature of the specimen being sprayed.

4. EXPERIMENTAL INVESTIGATION

The factors that can easily be altered independent of other factors are the wire feed and the spraying distance. Flame setting, regulation of compressed air, oxygen and acetylene influence each separately and together the flow, the atomizing and the nature of the flame so that their arbitrary setting is out of question.

The rotating-bending fatigue testing machine showed in Fig. 3 had the suitable bar model for spraying purposes. The speed of the machine is 2840 r. p. m. The maximum bending moment is 600 kgcm. The loading principle is shown in Fig. 4. The bar (Fig. 5 a) used in the machine was prepared for spraying by threading the steel bar in accordance with Figs. 5 b and 6 b. Two steel qualities were used: St 37.11 for preliminary tests (bars Nos. 1 to 5) and St 00. 11 (C % 0.29 H_B 139) for the final tests (bars 6 to 15). The spraying on bars Nos. 1 to 5 was carried out in such a way that the gun remained stationary and the bar was moved in a plane which was at a

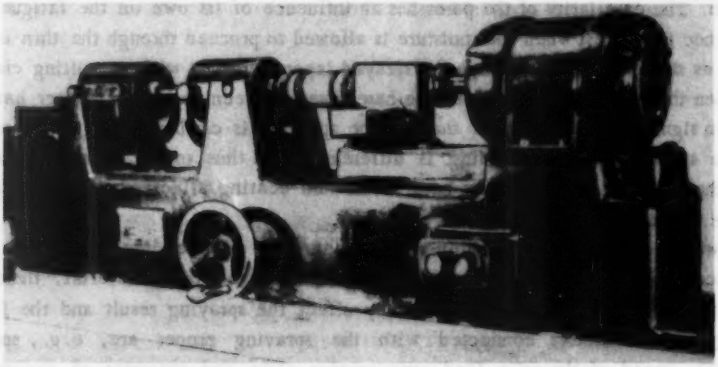


Fig. 3. Rotating-bending fatigue testing machine.

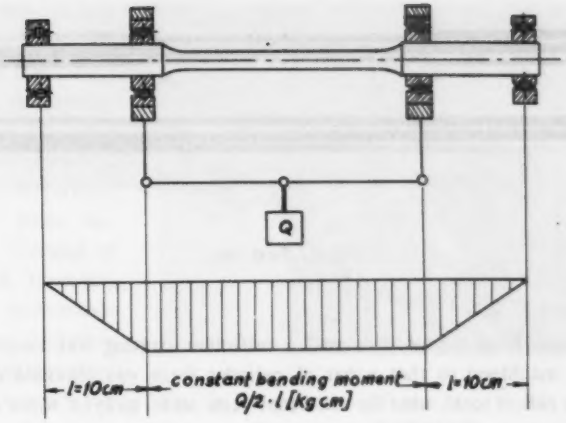


Fig. 4. Schematic drawing of loading in a rotating-bending fatigue testing machine.

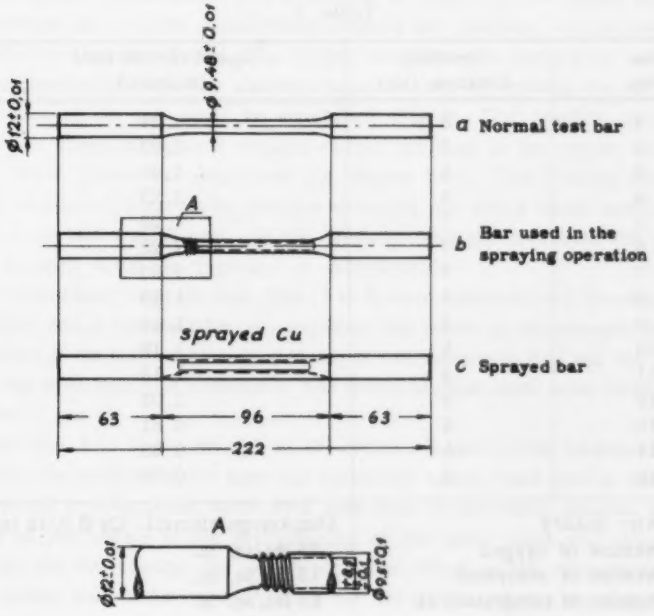


Fig. 5.

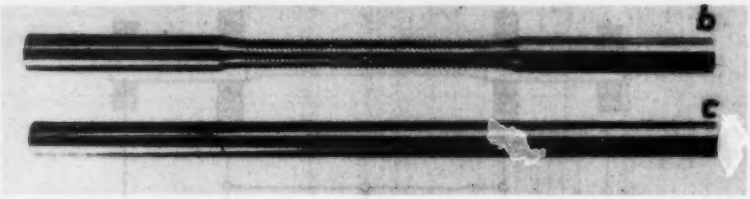


Fig. 6. Test bar.

constant distance from the nozzle until a sufficient coating was formed. After this the bars were machined so that a bar of cylinder form was obtained (Figs. 5 c and 6 c). The bars Nos. 6 to 15 used for the final tests were sprayed when rotating. The bar between the centres of the lathe was allowed to rotate at a constant distance from the nozzle and the gun in the carriage moved by degrees until a sufficiently heavy coating was obtained. After this the bars were machined to the same dimensions as bars Nos. 1 to 5. The spraying conditions for bars have been given in Table 1.

Table 1.

Bar No.	Spraying distance (in.)	Speed of wire feed (m/min.)
1	5	1. 14
2	5	0. 83
3	5	1. 43
4	3	1. 23
5	7	1. 23
6	7	1. 23
7	7	1. 23
8	3	1. 19
9	3	1. 19
10	5	1. 19
11	5	1. 19
12	5	1. 02
13	5	0. 81
14	5	0. 68
15	5	0. 76
Wire quality		Outokumpu electrol. Cu Ø 3/16 in.
Pressure of oxygen		35 lbs/sq. in.
Pressure of acetylene		15 lbs/sq. in.
Pressure of compressed air		65 lbs/sq. in.
Bars Nos. 1 to 5		St 37. 11
Bars Nos. 6 to 15		St 00. 11 H_B = 139, C = 0, 29 %

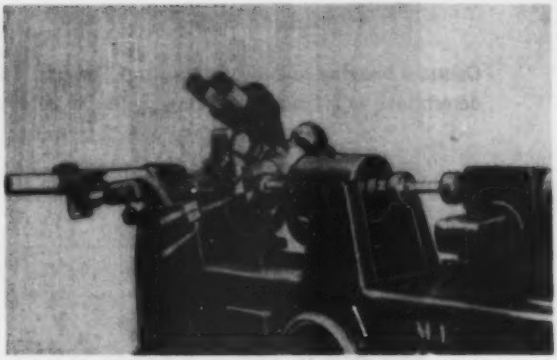


Fig. 7. Examination of test bar under the binocular microscope.

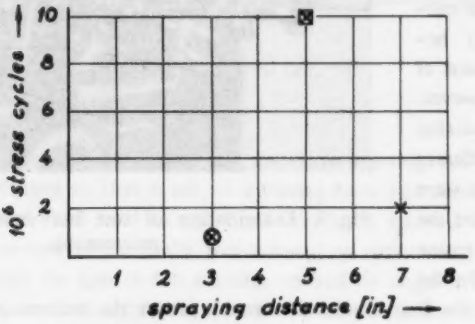
Although the fatigue strength of copper is uncertain and the stress cycles should be extended to 100 millions in the tests, it was, however, decided to take 10 millions as the limit because of the slowness of the machines. However, sufficiently comparable results for different spraying conditions were obtained. It was not the purpose to determine any Wöhler curve for the sprayed bars, but the first crack, discernable under the microscope, that appeared in the sprayed coating was considered the decisive factor. In this way we tried to find the most advantageous spraying condition. Consequently, the fatigue machine could not operate in the usual way according to which the bar would have broken and the switch would have immediately stopped the machine. A microscopic investigation was instead adopted. The fatigue machine was stopped for investigation and a binocular microscope was attached near the bar. By moving the carriage, the whole surface of the bar could be examined (Fig. 7). The bending moment that could not be exceeded without causing visible cracking in the copper coating, by using 10^7 stress cycles, was considered the fatigue limit. The bending moment was used as a measure of stress during the tests since the bar was a beam assembled of a copper coating and a steel core. As the dimensions of the bars were the same, the method as such could be regarded as comparable.

In the preliminary tests the bars (Nos. 1 to 5) were subjected to a bending moment of 105 kgcm and a comparative investigation was made of the strength of the bars as a function of the stress cycles. In this way it was possible to find out the directions in which the tests should be continued. The results of these tests have been presented in Tables 2 and 3.

For bars Nos. 6 to 15 the strength at 10^7 cycles was used as the measure of fatigue life. Since the number of the bars was relatively small, such bars as had already been subjected to alternating stress were also used at increasing stresses. It was not necessary to pay regard to the strengthening of the steel, since the object of investigation was the coating and its fatigue. The effect of the strengthening of the copper coating was tested on bars which had the same spraying conditions. One of the bars was gradually loaded and the surface was examined under the microscope. Thus, after 10^7 cycles the bar was run at a new load level by increasing the moment

Table 2.

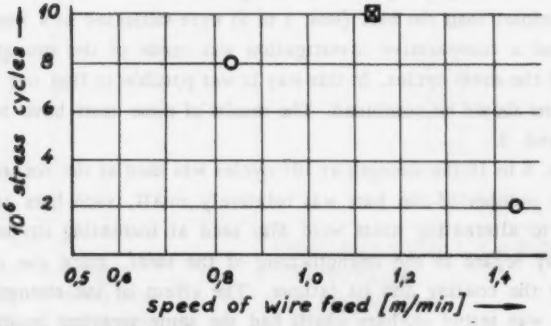
Constant bending moment 105 kgcm. The first fracture of the coating determined as a function of stress cycles at different spraying distances (wire feed ∽ 1. 2 m/min.



⊗ Steel failed first
⊠ Sustained 10^7 stress cycles
Preliminary tests on bars Nos. 1, 4, 5.

Table 3.

Constant bending moment 105 kgcm. The first fracture of the coating determined as a function of stress cycles at different speeds of wire feed (spraying distance ∽ 5 in.).



⊠ Subtained 10^7 stress cycles
Preliminary tests on bars Nos. 1, 2, 3.

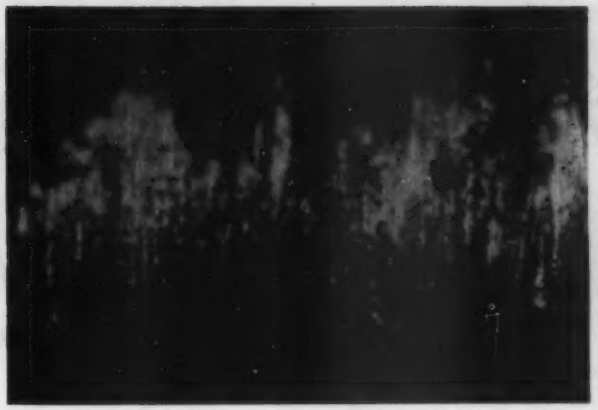


Fig. 8. Fatigue crack on copper surface. Magnified 70 times.

until a crack appeared. Another bar that had not yet been loaded was now subjected to this same load, and the failure of the coating occurred at the same level so that no strengthening had occurred.

In the microscopic investigations that were made between the rotating-bending fatigue tests it was possible to follow the alterations in the surface. On the whole the surface was even although the pores formed craters here and there. The bars that had been sprayed at slow wire feeds had the best surfaces. The influence of the oxides and the pores appeared on the surface mainly as a spotty machining finish. Pure copper and oxide had been cut from the surface in a different way. When the load approached the limit at which the coating broke, a certain kind of dusting phenomenon could be observed. On the surface of the sprayed copper there appeared dustlike particles which could be in some kind of row or as separate particles. The first visible fracture could then appear near such a row of dust particles, not always, however. When a visible fracture appeared, it usually wound from one crater to another proceeding round the whole bar (Fig. 8). However, such a crack did not mean that the base metal, the steel, would always at higher loads have broken at this point. Besides, the crack did not penetrate very easily until the base steel but seemed to stop, at least for some time, near the surface. The passage of the fracture through the coating was followed under the microscope. To this end a cross-cut was made of the bar at the circulating crack. The crack seemed to stop quite on the surface. Its passage could not be followed among oxide streaks and pores. It quite seemed as though the heterogeneous structure had eaten a crack in its own labyrinth in seeking for itself the easiest points of fracture. The "dust" observed on the surface of the bar can be explained in such a way that the pores had been partly deformed in machining and sprayed copper had entered into them from the edges, being then pressed out at

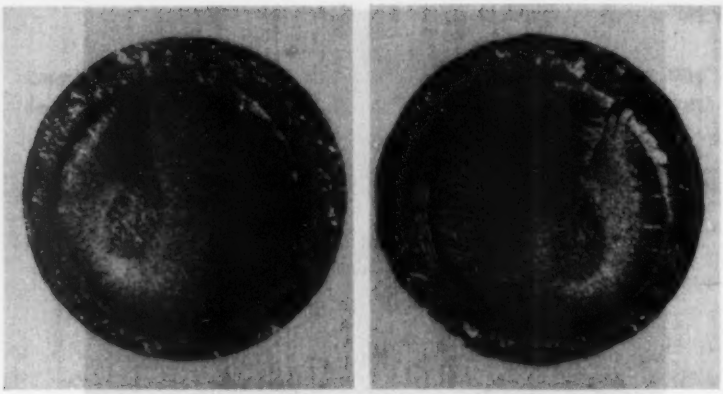


Fig. 9. Fatigue fracture on test bar.

alternating stress. It could also be thought that, owing to fatigue stress, the sprayed particles would grind against one another in the surface layer and the results of grinding would appear as "dust" on the surface.

Although the spraying process is considered a "cold" metallizing process, heat has, however, a considerable part in it [1, 3]. The dimensions of the specimen have also their own significance. A large specimen as spraying base is able to conduct heat over a wide range and acts as a cooler. When a small specimen is now subjected to a gas flow, it heats up vigorously. Although the temperature is so low that it does not cause any alteration in the crystal structure of the steel, it is, however, sufficient to affect the stress condition of the specimen. Owing to the threading and the sprayed copper layers, the steel is bonded to the coating during spraying. Now, the copper layers and the steel are cooling in a different way. The steel may warp during the spraying and the copper is chaining it into that form. Thus the steel may after machining be eccentric with regard to the sprayed coating. This was observed especially when the spraying was carried out at a distance of 3 in. This distance was too short for a specimen of the dimensions of the test bar - at least for continued spraying. The sprayed copper layers seemed dense and strong enough but the steel had suffered from the process so much that it broke before the fatigue limit of the copper coating had been reached. The most dangerous point for the steel fracture was the end of the thread on the bar before the rounding off to a shoulder of 12 mm in. diameter. This was due to the fact that in cooling the heat stresses tended to loosen the coating from the steel just at the juncture of the shoulders. Thus a weak point, which was still aggravated by the notch effect of the termination of the thread, remained between the shoulders and the sprayed copper. Heat effect also occurred on one bar that was sprayed at a distance of 5 in. Here the steel base had also warped

during spraying. The stress peak now produced led to a typical fatigue fracture following the rise of the thread (Fig. 9).

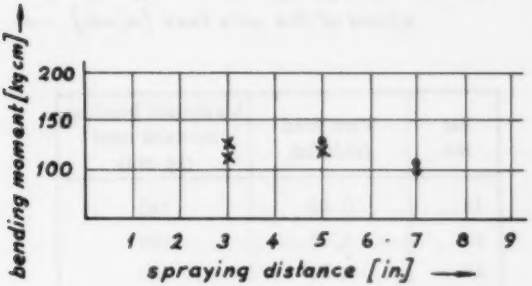
If the bar whose sprayed coating had cracked was further stressed, the result was fatigue of the steel base. The fracture that was now formed also followed the thread.

Owing to the heat effect the conditions on the test bar are, in fact, different from those on the wide steel frame. However, in investigating the influence of the spraying distance and the wire feed on the fatigue of the coating of test bars, it is possible to compare mutually these different factors.

The spraying distances at constant feeding seem to be, within certain limits, inversely proportional to the fatigue strength. The graphical presentation of the test results shows the spraying distance of 3 in. to be an exception but, because of the above-related heat effect, the result is too disadvantageous. The results have been presented in Table 4.

Table 4.

Dependency of fatigue strength on the spraying distance. Speed of wire feed ~ 1.2 m/min. 10^7 stress cycles.



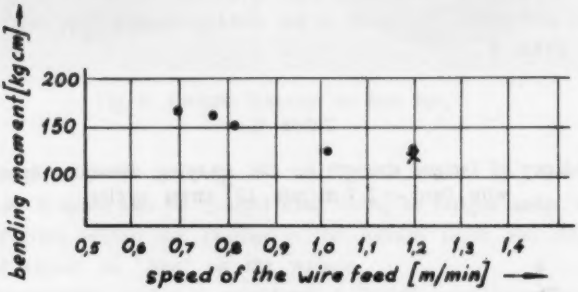
Bar No.	Spraying distance (in.)	Maximum bending moment used (kg cm)
8 x)	3	125
9 x)	3	110
10 x)	5	120
11	5	125
6	7	105
7	7	100

x) at the next stress the steel fractured.

The speed of the wire feed is also, within certain limits, inversely proportional to the fatigue strength when the spraying is done at a constant distance. The results of these tests are presented in Table 5.

Table 5.

Dependency of fatigue strength on the speed of the wire feed. Spraying distance ~ 5 in. 10^7 stress cycles.



Bar No.	Wire feed (m/min)	Maximum bending moment used (kg cm)
14	0.68	165
15	0.76	160
13	0.81	150
12	1.02	125
11	1.19	125
10 x)	1.19	120

x) at the next stress the steel fractured.

How can these things be understood by examining the metallizing process? When the speed of the wire feed is constant and the spraying distance is altered, the conditions change in the metallizing cone. The flow is gradually dispersed and the speed of the particles decreases with increasing distance from the nozzle. Thus the striking force of the particles against the base diminishes, cooling is rapid and the plasticity weakens. The interlocking of the particles and their bonding to the steel

frame deteriorates and, on the basis of this, it is also possible to understand the decrease in strength at fatigue stress.

When the feeding speed is varied at a constant distance from the base metal, the atomization occurs in different ways. At a high feeding speed the melting capacity of the flame is stressed to the utmost and the melting copper may loosen even as macroparticles. When the feeding speed is reduced, less molten metal comes into the flow and the atomization is more perfect. Of what significance is this to the fatigue strength? Although the sprayed metal that has oxidized owing to small particles increases in amount, the thin copper mist forms more homogeneous layers, it fills better the cavities of the base and gives better support to the base material. Thus the fatigue strength of the layer as well as that of the whole structure increases.

5. SUMMARY

The properties of sprayed copper, the influence of the steel surface on spraying and the corrosion-resistant influence of sprayed copper on steel were examined. The practical tests for investigating the fatigue strength of sprayed copper were carried out under laboratory conditions in a rotating-bending fatigue testing machine (Fig. 3). A copper layer was sprayed on the surface of a steel test bar (Fig. 5, 6). The stress that could be sustained for 10^7 load cycles without producing a crack, visible under the binocular microscope, was regarded as the fatigue strength of sprayed copper. The effects that had occurred in the sprayed coating were examined under the binocular microscope during the fatigue test. On the basis of the observations made in the fatigue tests it could be stated that both the wire feed and the spraying distance were, within certain limits, inversely proportional to the fatigue strength of sprayed copper (Tables 4 and 5).

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